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Diver cores were collected from various locations within the SAX04 site from 21 September to 3 November 2004 and compressional wave speed and attenuation were measured every centimeter at 400 kHz. Although measured values of sound speed and attenuation fall within established ranges for archived data from similar medium quartz sands, fluctuations in measured values were observed in the data that can be explained by the pattern of storm events during the experiment. Three significant storm events occurred during the period in which cores were collected: a category-4 hurricane, a tropical storm, and an early-winter cold front. Following these events values of sound speed initially increased, but then later decreased; values of sound attenuation did not show this pattern, but were generally lower (mean = 92.1 dB/m) than values measured

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SPATIAL AND TEMPORAL VARIATIONS IN SEDIMENT COMPRESSIONAL WAVE SPEED AND ATTENUATION MEASURED AT 400 KHZ FOR SAX04

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Diver cores were collected from various locations within the SAX04 site from 21 September to 3 November 2004 and compressional wave speed and attenuation were measured every centimeter at 400 kHz. Although measured values of sound speed and attenuation fall within established ranges for archived data from similar medium quartz sands, fluctuations in measured values were observed in the data that can be explained by the pattern of storm events during the experiment. Three significant storm events occurred during the period in which cores were collected: a category-4 hurricane, a tropical storm, and an early-winter cold front. Following these events values of sound speed initially increased, but then later decreased; values of sound attenuation did not show this pattern, but were generally lower (mean = 92.1 dB/m) than values measured five years ago at the SAX99 site nearby (mean = 177.5 dB/m). Values of sediment sound speed measured at the SAX04 (mean velocity ratio = 1.162) were generally greater than those measured at the SAX99 site (mean velocity ratio = 1.155). Values of coefficient of variation for sediment sound speed were lower for SAX04 measurements (0.55%) than SAX99 measurements (0.70%). Lower values of sound attenuation measured at the SAX04 site was probably due to a lack or absence of shell fragments that may have been segregated by the sediment resuspension and settling during and after storms. The roles of sediment transport, grain size, grain sorting, porosity, and density in controlling sediment compressional wave speed and attenuation at the SAX04 site are discussed.

1 Introduction

Sediment compressional wave speed and attenuation are important parameters required in assessing acoustic scattering from the sea floor [1,2]. The contrast between the sound speed within the sediment and the sound speed in the overlying water is the chief characteristic determining the fate of acoustic energy reaching the sea floor. The magnitude of the attenuation of the acoustic energy within the sediment determines to what depth the sound penetrates the sea floor (and how much scattered energy is reradiated back out of the sea floor). Moreover, fluctuations in sediment sound speed may be responsible for the scattering of acoustic energy penetrating into the sediment.

As part of the geoacoustic measurements collected by the Naval Research Laboratory during Sediment Acoustics eXperiment 2004 (SAX04), sediment compressional wave speed and attenuation were determined at 400 kHz on 58 diver cores. The cores were collected throughout the experiment, from 21 September to 3

November and measurements were made aboard ship within 24-36 hours after collection. Consequently, the measurements exhibit both spatial and temporal variations in these parameters for the SAX04 site.

The important factors controlling sediment compressional wave transmission in sands are porosity, grain size, grain sorting, grain shape, grain packing and mineralogy; although, porosity and grain properties are correlated factors [3]. Previous studies of the area off Fort Walton Beach, Florida show the sediment to be a relatively homogeneous, moderately well sorted, medium quartz sand [4]. Differences in sound speed transmission within the sediment are thought to be essentially a matter of grain packing, which can be changed by bioturbation and hydrodynamic events [5]. Because there were three major storms during the execution of SAX04, the effects of reconfiguring the grain-to-grain structure by storm resuspension and sedimentation may be examined.

2   Methods

Diver cores that were made from 5.9-cm-inside-diameter, clear polycarbonate tubing cut into 48-cm lengths were used to collect the sediment samples from various locations within the SAX04 experiment site. Each core was carefully handled and kept upright during the collection, the sealing of the top and bottom, the recovery through the air-water interface, the storage in the temperature-controlled laboratory, and the acoustic measurements. Upon recovery, each core was sealed with tape to prevent draining of the overlying water and the level of the sediment-water interface was marked on the core to monitor settling.

After allowing the cores to equilibrate to laboratory temperature for at least 24 hours, sediment compressional wave speed and attenuation were measured directly through the core liner with "earmuff" transmit and receive transducers, function generator, pulse generator, dual band-pass filter, and digital storage oscilloscope as depicted in Fig. 1 [6]. Measurements were made at 400 kHz at 1-cm increments downcore.

Figure 1. Equipment used to measure compressional wave speed and attenuation (left) and a close-up view of the "earmuff" transducers with a core inserted between the transducers (right).

Sound speed ratio is calculated as the ratio of sound speed in sediment to sound speed in the overlying water. Sediment compressional wave attenuation values are expressed as dB/m and normalized to the acoustic frequency as dB/m·kHz (k, after Hamilton) [7]. Sediment porosity was measured at 2-cm intervals after transport of the cores to a shore-based laboratory from one to 33 days after collection by divers. Bulk density was calculated from porosity values and measurement of grain density. Grain size distribution was determined by dry-sieving for sand- and gravel-sized particles and pipettes for the silt/clay fraction.

3 Results

Compressional wave speed (V_P) ratio and attenuation as a function of sediment depth is illustrated in Fig. 2. Low values of V_P ratio correspond to mud layers and flasers [8] and these features as well as the attenuation values associated with them will be disregarded in all of the subsequent figures, tables, and results for the purpose of this analysis of compressional wave energy in sand. Sediment sound speed increases slightly downcore to about 15 cm depth, and is generally constant below that depth. Sediment sound attenuation exhibits a slight increase throughout the measured depth. Values of attenuation show great variability in the top 14 cm, and these high values that depart from the overall trend are probably indicative of scattering of the 400-kHz sound by the mud-sand interfaces of mud layers and flasers. Note the relative absence of high attenuation values below the sediment depth where the mud is found in Fig. 2.
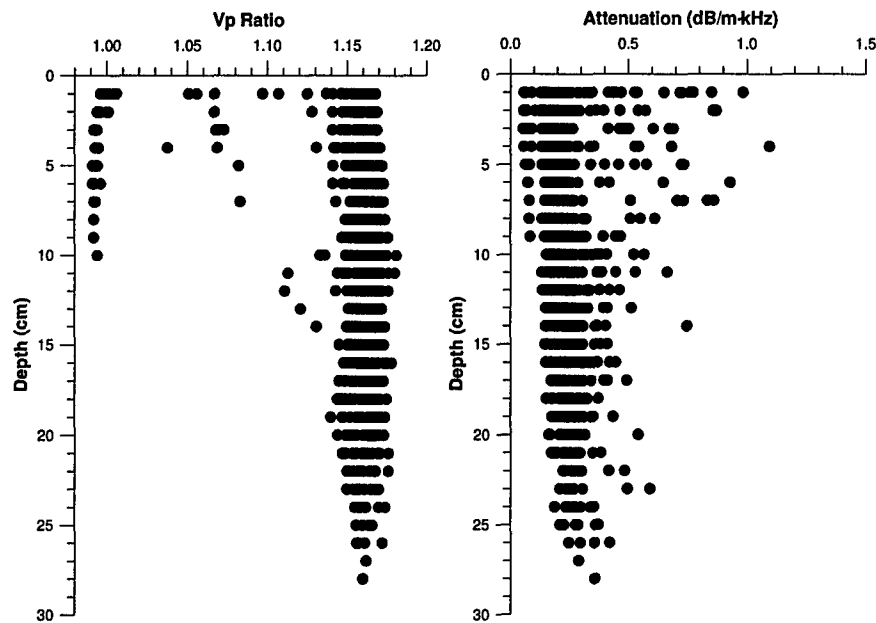
Figure 2. Compressional wave speed (V_P) ratio (left) and compressional wave attenuation (right) as a function of depth in the sediment for the SAX04 site.

During SAX04 three significant storm events occurred: Hurricane Ivan, a category 4 storm, made landfall 100 km west of the experiment site on 16 September; tropical storm Matthew approaching from the west produced strong southwest to west winds during 8-10 October; and a cold front passed through the area on 2 November. These storm events effectively divided the experiment into four periods, which were determined from patterns of sediment acoustic data collected from cores (Table 1). The average sediment sound speed excluding obvious mud layers is 1775.6 m/s calculated for 23°C, 35 ppt, and atmospheric pressure and the average sound speed ratio is 1.162 with a coefficient of variation (CV) of 0.55%.

Table 1. Values in *sand* of compressional wave speed (V_P), compressional wave speed ratio, and compressional wave attenuation (dB/m, dB/m·kHz) for four periods during SAX04; values of coefficient of variation (%) for the data; values of the data for all periods of SAX04.

Period	Dates	V_P (m/s)	V_P Ratio	Att. (dB/m)	k (dB/m·kHz)
post Ivan	21-30 Sep	1779.9	1.164	87.8	0.22
pre Matt	1-5 Oct	1770.6	1.158	99.9	0.25
post Matt	12-31 Oct	1776.0	1.162	90.2	0.23
post cold front	3 Nov	1782.7	1.166	89.8	0.23
All		**1775.6**	**1.162**	**92.1**	**0.23**
post Ivan	21-30 Sep	0.60		21.07	
pre Matt	1-5 Oct	0.55		31.02	
post Matt	12-31 Oct	0.50		31.26	
post cold front	3 Nov	0.40		21.56	
All		**0.55**		**30.26**	

Immediately following Hurricane Ivan, suspended sediments settled and fine-grained mud brought from the lagoon north of the barrier island was deposited on top of the freshly settled sand. For 14 days following Ivan (post Ivan), benthic fauna appear not to have begun to recover from the catastrophic resuspension of the sediment in which they were living. Indeed, with the turbulent fluidization of their habitat sustained for several hours, whatever fauna that were not destroyed were irretrievably buried. In the next 5 days before the effects of Matthew began to be felt, values of sediment sound speed and attenuation appeared to change, perhaps due to a delayed recovery response of the benthic fauna. There is a significant difference ($\alpha \ll 0.001$) in t-tests of means for sound speed and attenuation values between the four successive periods, with the exception of the attenuation values between the post-Matthew and post-cold-front periods.

Average sediment sound speed ratio at the SAX04 site (1.162) was greater than the average value at the nearby SAX99 site (1.155); average sediment sound attenuation at the SAX04 site (92.1 dB/m) was less than the average value at the SAX99 site (173 dB/m) [4]. Moreover, there were significant statistical differences (t-test: $\alpha \ll 0.001$) between the average SAX99 sound speed ratio and each of the average sound speed ratios for the four SAX04 periods. The average SAX99 sound attenuation value was also statistically different from any of the average SAX04 sound attenuation values for the

four periods. The coefficient of variation was lower for SAX04 sound speed values (0.55%) than that for SAX99 sound speed values (0.70%). Coefficients of variation for SAX04 and SAX99 sound attenuation values were similar (30.3 *vs.* 29.9%). A comparison of SAX04 and SAX99 sediment properties of sound speed ratio, sound attenuation, porosity, mean grain size, and sorting are displayed in Table 2. SAX04 sand has faster and less variable sound speed, less attenuation, finer and less variable mean grain size, and is slightly better sorted than SAX99 sand.

Table 2. Comparison of measured properties of SAX04 and SAX99 sands. CV(%) in parentheses.

Site	V_P ratio	Att. (dB/m)	Porosity (%)	MGS (ϕ)	Sorting (ϕ)
SAX04	1.162 (0.55)	92.1 (30.3)	36.7 (1.84)	1.51 (11.3)	0.61 (9.76)
SAX99	1.155 (0.70)	173.0 (29.9)	37.2 (1.92)	1.27 (13.3)	0.63 (8.06)

4   Relationships of sound speed and attenuation to physical properties

There are established empirical relationships between sound speed and sediment physical properties such as porosity, density, and grain size [9-11]. For sands, sound speed typically increases with decreasing porosity, increasing mean grain diameter, and decreasing sorting (a measure of dispersion around the mean grain size). Relationships between sound attenuation and sediment porosity, density and grain size are poorly defined, though the presence of coarse grains that can scatter high-frequency sound can contribute to high attenuation values [12].
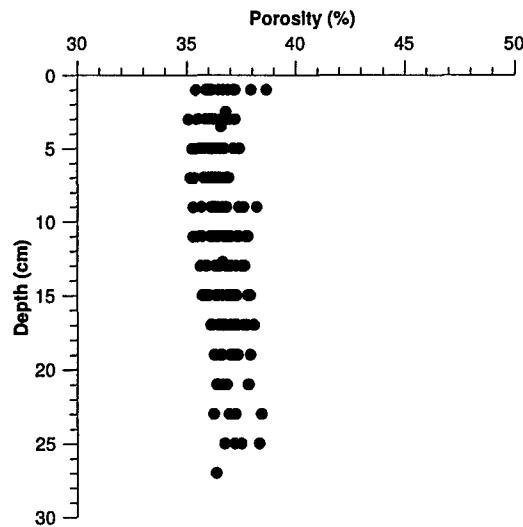

Figure 3. Sediment porosity (%) as a function of depth in the sediment for the SAX04 site.

Based on measurements on the same cores from which the sediment sound speed was measured, porosity, density and grain size of the SAX04 sediment exhibit little variability throughout the experiment site. Sediment porosity profiles (exclusive of high-

porosity mud layers) from 22 of the 58 collected cores exhibit only small variations within the sandy sediment (Fig. 3). Sediment bulk density profiles (not shown) exhibit the same, though inverted, pattern. Sediment mean grain size profiles (exclusive of mud layers) of 11 of the 22 cores assayed for porosity and bulk density also show little variation with sediment depth or location within the site (Fig. 4). Sediment sorting also shows little variation with depth in the sediment or location (Fig. 4). Moreover, the average value of sediment porosity at the SAX04 site, derived from all 11 locations fall within the range of variation for each site; average values of mean grain size show slightly more variation due to mud clasts (Fig. 5). Thus, it is unlikely that differences in sediment sound speed portrayed in Fig. 2 are due to spatial variability of sediment properties within the experiment site.
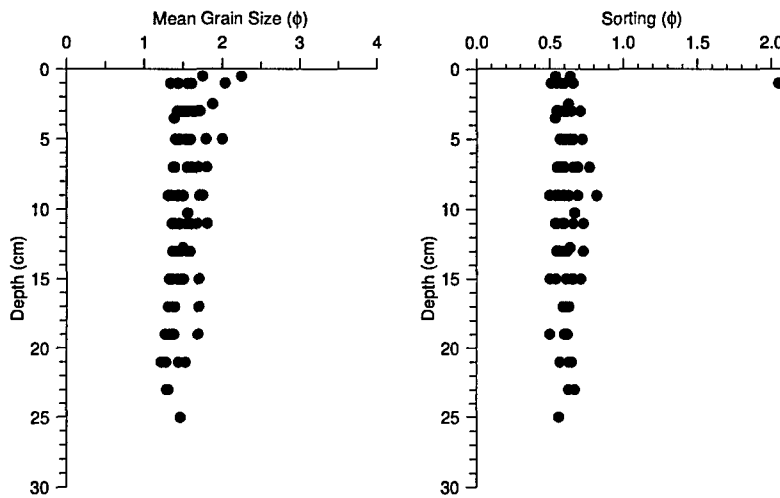

Figure 4. Sediment mean grain size (ϕ) and sorting (exclusive of mud layers) as a function of depth in the sediment for the SAX04 site. Phi (ϕ) units are $-\log_2$(dia. in mm).
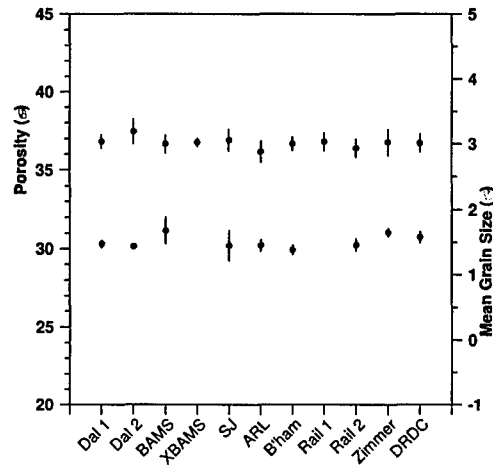
Figure 5. Sediment porosity (%) and mean grain size (φ) of *sand* as a function of location within the SAX04 site. Bars are ± 1 standard deviation. Phi (φ) units are –log$_2$(dia. in mm).

Based on the an analysis of historical wave data from an offshore NOAA data buoy [8] and the changes in the sound speed profiles displayed in Fig. 2, we believe that at least the top 20 cm of sand was suspended during Hurricane Ivan and redeposited upon the passing of the storm to the north. Indeed, a slight fining-upward trend in mean grain size is evident in Fig. 4, indicating the grain sorting that would occur during settling under the waning effects of waves and currents from the passing storm. Immediately after the storm, the arrangement of the freshly settled grains should have presented a low-density, high-porosity packing of the sand. Over time, with the resumption of biological mixing from benthic infauna, the packing should have changed to a higher density conformation, especially in the top 10-15 cm where the infauna predominantly reside.

Our results, however, indicate that changes in porosity and density were not commensurate with the fluctuations of sediment sound speed. Thus, the changes in the sediment effected by storms and bioturbation, as evidenced by changes in sediment sound speed and attenuation, had little effect on the spaces among sand grains. This conclusion relies on the assumption that the sediment porosity, density, and grain packing were not altered during the interim between the time the cores were logged on board and the cores were later assayed for water content ashore. Although precautions were taken during storage and transport (refrigeration and isolation from agitation), some settling may have occurred in the interim. The sediment-water interface was marked on the core liner upon recovery of the core and before the core was logged acoustically. The amount the core sediment settled was noted immediately before analysis for water content. Of the 22 cores assayed for water content, 16 showed some amount of settling that varied from 1-5 mm. Adjusting for the length of each core, settling varied from 0.6-3.3 % of the core volume and averaged 1.3 % for the 16 cores. Of the six cores with volume changes due to settling greater than 1 %, three had mud layers or clasts that, as de-watering occurred, contributed to the settling. Settling may have been facilitated by bioturbation more than any other factor, because the cores collected immediately post Ivan did not exhibit evidence of bioturbation or settling. Until porosity can be

determined immediately after acoustic logging, the correlation between sediment porosity and sound speed is uncertain for these data.

An alternate explanation for the temporal variations in sediment acoustic properties is that differences in the grains are responsible. That is, the grain shape or geometry of grain aggregations, influenced by the settling of grains during the post-storm periods, may control sound speed and attenuation in sediments. During the waning of the storms, the larger and more spherical grains settle first; the finer and more platy grains settle later. This scenario would result in a mixture of smaller spherical and larger platy grains near the surface and a dearth of platy grains deeper in the sediment at the beginning of SAX04. Such a segregation of grain shapes would not necessarily be accompanied by differences in average values of porosity or grain size, but might result in faster sound speeds and lower attenuation in the fine/platy aggregation than in the coarse/spherical grains deeper in the sediment. Conceivably, bioturbation would tend to destroy such a vertical segregation of grain shapes and tend to bring sound speed and attenuation values back to those values typical of well mixed sediments. According to this scenario, (1) the locus of change in sound speed and attenuation before and after storms would be the uppermost centimeters where the fauna are the most active and (2) the biogenic mixing response to the storms would be more rapid following weaker storms and delayed or retarded following catastrophic storms (e.g., Hurricane Ivan). This is, in fact, the pattern exhibited by the data in Fig. 2 and Table 1. An examination of the grain shape of SAX04 sediments as a function of depth in the sediment is warranted in order to substantiate these observations. Furthermore, a physical model to explain the acoustic behavior of the fine/platy aggregation is required to validate these assumptions.

Concerning the presence of calcareous shell fragments and their effect on sound attenuation: we do observe a significant ($\alpha \ll 0.001$) depletion in gravel-size grains, which are predominantly mollusk shells and shell fragments, in SAX04 sediment when compared with nearby SAX99 sediment (0.05% vs. 0.72%, respectively). This observation and the observation of lower attenuation in SAX04 sediment when compared with nearby SAX99 sediment (Table 2) imply that scattering from shells and shell fragments contribute to acoustic attenuation.

Acknowledgements

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